Main Injector Quad Length Ratios and Current vs Tune Parameters

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We would like to come up with a paramertization to relate the currents in the F and D quad buses to the tune of the Main Injector. In order to accomplish this we need to be able to model the correct "effective magnetic lengths" of the three types of quadrupoles such that we specify only the F and D momentum independent gradients in the model.

But, first a little history...

<u>MI-17 Lattice design:</u>

The initial Main Injector lattice design (MI-17) used three quad lengths for the arc half-cell, dispersion suppresser half-cell, and the transition half-cell. The arc half-cell quad had a magnetic length of 2.1336 meters, the dispersion suppresser quad had a magnetic length of 2.953 meters, and the transition half-cell quad was made up of half of the arc quad plus half of the dispersion suppressor quad to make a 2.5433 meter quad. This produced the ratio of lengths quoted in the TDH (chapter 3.1, page 34) of

1 : 1.1920238 : 1.384048.

The goal is to produce the two new type of quads, the 100" and 116", such that the ratio of the integrated strengths of these quads to the 84" quads met the above ratio at 120 GeV/c. All quads are configured on one of two quad buses, focussing or defocussing. If the steel going into each of the new quads is identical, then it is sufficient to match the ratio of the lengths.

The momentum independent strength for the linear lattice (no errors) was specified as K1QF = 0.0403538 [1/m^2] and K1QD = -0.0394974 [1/m^2] which gave tunes of Qx = 26.410 and Qy = 25.413. When the linear lattice was tuned to the now nominal tunes of Qx = 26.425 and Qy = 25.415 the quad strengths changed to K1QF = 0.04036935 [1/m^2] and K1QD = -0.03940270 [1/m^2].

<u>The Initial MI-19 Lattice:</u>

The initial MI-19 version of the MAD description incorporated, not only the magnetic length of the dipoles and quads, but the physical length of all dipoles, quads, and correctors, and explicitly defined each element by name. It used the following quad steel and magnetic lengths:

quad	steel length	magnetic length
BQB	2.1336m (84.00")	2.1336m (84.00")
IQC	2.53939m (99.976")	2.54329m(100.13")
IQD	2.94518m (115.952")	2.953m (116.26")

with the length ratios of

84/84 : 100.13/84 : 116.26/84	and	116.26/100.13
1 : 1.1920238 : 1.384048		1.1610905

The magnetic lengths were retained from the origional lattice while the steel lengths were taken from early drawings of quad mini-straight layouts based upon an initial analysis of Main Injector quad steel length requirements [1]. Here, the steel lengths were used to account for physical slot lengths while the magnetic length was used to determine the integrated gradient. The momentum independent quad strengths to produce the nominal tune in the linear lattice were:

K1QF = 0.04036935 [1/m^2]　　　k1QD = -0.03956239 [1/m^2].

The integrated gradients, B'L, that are required at injection, 40 GeV/c, 120 GeV/c, and 150 GeV/c for the IQC's in this linear lattice are given by K1QF*Leff*(P/.2997925) in units of T-m/m.

Momentum	B'L(f)	B'L(d)
8.8889	3.0442	-2.9834
40	13.6989	-13.4251
120	41.0968	-40.2753
150	51.3710	-50.3441

When standard errors were incorporated [2] and the lattice was retuned to the nominal tunes, the quad strengths became K1QF = 0.04036346 [1/m^2] and K1QD = -0.03951398.

Problems with quad lengths:

A small set of BQB (84") and BQA (52") Main Ring quads were measured in 1986 with the VAX measurement system and few BQA's were measured again in 1994 with the new UNIX based system [3]. Based upon the 1986 measurements of 2 BQB's the effective length of the 84" BQB quad was determined to be 20 mm (10 mm/end) shorter than the physical length of 2.1336 meters. This means the magnetic length to be used in lattice calculations should be 2.1136 meters (83.2126"), **not** the 2.1336 meters used in the initial MI-19 lattice description.

To keep the design ratios based upon effective length of the BQB, the steel lengths of the IQC's and IQD's should be 2.5394 meters (99.976") and 2.9452 meters (115.953"), respectively[2].

Subsequent analysis in 1994 calculated the effective length of the BQB based upon the ratio of the strengths of the BQB to the BQA and determined an effective length of 83.397" [3]. According to the analysis in Ref. [3] the steel lengths of the IQC and IQD would need to be 110.014" (2.5404 meters) and 116.028" (2.9471 meters).

As built lengths of IQC's and IQD's:

However, after reviewing the IQC travelers it appears that the majority of the IQC quads were made to a steel length of 99.945" (2.5386meters) +/- 0.030" (i.e. half a lamination). The end contribution was measured to be -8mm per end which makes the effective length of the IQC 99.315" (2.5226 meters). If the end contribution on the BQB's were -10 mm the ratio of effective lengths would be 1.1935, too large. If we assume that the BQB has the same -8 mm end contribution as the IQC's (to give a effective magnetic length of 83.37" or 2.1176 meters) then the ratio of IQC/BQB effective lengths is 1.191207, much closer to the design ratio.

Assuming the same -8mm end contribution for the IQD's and assuming the ratio between the IQC/IQD's is the same as the TDH we should stack for an effective length of 115.31" (2.9289 meters) which implies a steel length of 115.94" (2.9449 meters).

However, the IQD's were stacked to a length of 116.00" (2.9464 meters) and a presumed effective length of 2.9304 meters (115.37").

New MI-19 quad lengths and strengths:

MI19 was changed to reflect the measured steel lengths of the BQB, IQC, and IQD. A constant -8mm end contribution on all quads was assumed, as summerized in the following table.

quad	steel length	magnetic length
BQB	2.1336m (84.00")	2.1176m (83.37")
IQC	2.5386m (99.945")	2.5226m (99.315")
IQD	2.9464m (116.00")	2.9304m (115.37")

These give the ratios 1 : 1.1912070 : 1.383831. These are clearly not quite the "design values" , but that's life.

With this modification to MAD, the required momentum independant quad strengths to obtain the design (or base tunes) with a linear lattice (no errors) are:

K1QF = 0.04068110 [1/m^2]   K1QD = -0.03980760 [1/m^2] .

To check that this change in the required quad strength for the linear lattice due to the change of effective magnetic length is reasonable, I compare the total change in effective lengths before and after the lattice change to the change in required strength:

quad	old length	new length	change	#quads	total change
BQB	2.1336m	2.1176m	-0.016m	X 128	= -2.048 m
IQC	2.543297m	2.5225m	-0.020797m	X 32	= -0.665504m
IQD	2.953m	2.9304m	-0.0226m	X 48	= -0.0226m

This is a reduction 2.736104 m out of a total effective magnetic length 496.230304m or about 0.6% decrease in total length. One would expect the required quad strength to increase by about the same amount. The focussing quad strength increased by about 0.77% while the defocussing strength increased by about 0.62%.

Magnet Measurements:

Currently only a few of the BQB magnets have meen measured since they are still in use in Main Ring. These will be measured during the long shutdown. All of the IQC quads have been constructed and measured. All of the IDQ's have been constructed and measured.

To get an idea what magnitude of current these new values of strengths correspond to, I looked at the IQC028 (taken as a typical IQC quad) strength curve for the ramp up. I fit the low current region between 200A and 1000A with a straight line and the region between 2000A and 4000A with a second order ploynomial to take into account saturation. The data and fit for this quad are shown in Figure 1 and the results of the fit are:

I(200-1000) = -1.26296 + 68.6367*B'L and
I(2000-4000) = 166.837 + 59.1461*B'L + 0.1366*(B'L)^2.

The 2000-4000 Amp fit is not too bad. As an example, calculate the current corresponding to a B'L of 43.60615 T and we get 3005.715. The actual current was 3006.62 a difference of about .9 Amps or 3 parts in 10,000.

To get an idea of the required currents, in Amps, at various points in the cycle, we have:

Momentum	K1QF	K1QD
8.8889	207.58	-205.62
40	938.50	-920.85
120	2826.61	-2764.66
150	3563.58	-3483.07

The mean strength for all the IQC's was calculated and at 3000 A it is 43.4735 T-m/m. The mean strength of the current sample of 19 IQD's at the same current is 50.5350 T-m/m. The ratio of the mean strength of the IQD/IQC is 1.16243. This says either the mean strength of the IQD's is too strong or the IQC's are too weak. But, since the IQD length was based upon the IQC measurements, the ratio being larger than the desired ratio of 1.1610905, indicates the IQD is too strong. This excess strength corresponds to

2.2 laminations in length or about 12 units of systematic error in the strength of the IQD's. Another way of looking at the excessive strength is that the 8mm effective end contribution on for the IQD in 1.7 mm too long. From this data, however, one cannot tell if it is indeed a length problem or different steel properties or too small of sample of the IQD's. What impact does this excessive strength (which could be modeled as an end contribution) have on the required power supply current? The other question that could be asked is what effect does a systematic error of 12 units in the IQD as compared to the IQC have on the lattice. I will not answer that here.

The lattice has been constructed to allow independent control of end contributions. If the end contribution of any of the three style quads is larger by 2mm from the -8mm per end assumed here, the change in the required current to give the nominal tunes at 150 GeV/c are:

dIQF(84) = +4.31 Amps or 12 parts out of 10,000
dIQF(100)= +1.07 Amps or 3 parts out of 10,000
dIQF(116)= +1.08 Amps or 3 parts out of 10,000.

The changes in the QD bus are on the same order of magnitude.

Relate tune to quad strength:

The required quad strength K1QF and K1QD to produce a tune **change** of dQx, dQy from the nominal operating tunes of 26.425 , 25.415 is given by:

K1QF = K1QF(0) + dKf
K1QD = -K1QD(0) + dKd

where K1QF(0) and K1QD are the strengths for the nominal operating tunes, and

dKf = +0.001022 dQx + 0.000185 dQy
dKd = -0.000196 dQx - 0.001008 dQy

are the required change in quad strengths. It should be noted that this relationship is for a linear uncoupled lattice.

Summary:

1. The MI-19 steel and magnetic lengths have been changed to reflect the as built dimensions and magnetic measurements of the BQB's , IQC's and IQD's. The end field contribution is taken to be the same for all quads, i.e. -8 mm/end.

2. Two expressions for current vs strength for IQC028 were obtained, a linear expression for currents between 200 and 1000A and a quadratic expression for currents between 2000 and 4000 amps to take into account saturation. This procedure needs to be repeated for the mean strength measurements for each of the BQB's, IQC's, and IQD's to verify correct ratios. This procedure needs to be performed as well for the down ramp for use with deacceleration.

3. The ratio of <IQD's> to <IQC's> integrated strength is higher at all energies, but the discrepancy is largest at 3000 Amps. This corresponds to less than 2 mm change in effective length and corresponds to less than 3 parts in 10,000 change in quad bus current.

4. An expression for the change in quad strength required for any given change in tune from a nominal value was found.

[1] Dave Harding, MI Note 117, "Initial Determination of Main Injector Quad Steel Lengths", 1991.

[2] Shekhar Mishra, results from TEAPOT calculation using MI-19 lattice.

[3] Bruce Brown, MTF-94-0044, "Determination of Stacking Length for IQC Quadrupoles", Aug. 1994.